Development and Testing of Embedded Gridding within the Regional Ocean Modeling System: Interactions Between Near-Shore and Off-Shore Currents and Materials

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LONG-TERM GOALS

The goals of this project are (1) to improve the algorithms for computational modeling of local oceanic regions that have significant interactions with their surrounding regions and (2) to simulate and understand the controlling processes for dynamical coupling and material exchanges between near-shore regions over continental shelves and adjacent off-shore regions.

OBJECTIVES

The objectives of this project are (1) to continue the development of the Regional Oceanic Modeling System (ROMS) with respect to its hydrodynamic algorithms, physical transport parameterizations, and range of represented biogeochemical processes; (2) to further refine and apply its nesting capabilities using adaptive open-boundary conditions (OBCs) for imposing large-scale boundary data; (3) to develop a multi-level, multi-grid embedding capability in ROMS for simultaneously calculating solutions on coarse-resolution (parent) and fine-resolution (child) grids; (4) to use ROMS to investigate dynamical coupling and material transport between near-shore and off-shore regions along the North American West Coast (NAWC), with special attention to Monterey Bay (MB), the Southern California Bight (SCB), and the GLOBEC NE Pacific region off Oregon and Northern California; and (5) to use ROMS to investigate the response of the NAWC region to remote forcing in the Pacific basin and the influence of NAWC coastal phenomena (*e.g.,* upwelling) on Pacific basin-scale phenomena.

APPROACH

The primary design goal for ROMS is to produce limited-area, high-resolution, realistic coastal simulations in an efficient manner on parallel computers. The technical approach is computational simulation of oceanic fields for velocity, temperature, and salinity; chemical concentrations of nutrients, O_2, CO_2, etc.; planktonic populations; and mobile sediments. ROMS is based on the hydrostatic Primitive Equations in terrain-following curvilinear coordinates with a free upper surface. The boundary-value problems that are our focus are for various regional domains along the NAWC (*e.g.*, Marchesiello *et al.*, , 2002) with specified surface forcing fields and boundary data, taken either from climatology or from the output from a whole-Pacific ROMS configuration. The outermost boundary data are imposed by adaptive OBCs (Marchesiello *et al.*, , 2001), and we have developed and implemented a hierarchical embedding capability for the local, fine-resolution grid in a sub-domain within the coarse-resolution grid spanning the entire domain (Penven *et al.*, , 2002a). Key researchers at UCLA on this project are Xavier Capet (newly arrived), Patrick Marchesiello, James McWilliams, Pierrick Penven (now departed), and Alexander Shchepetkin, as well as Meinte Blaas, Hartmut Frenzel, Nicholas Gruber, and Keith Stolzenbach for biogeochemical and sedimentary issues. Laurent Debreu (LMC, Grenoble, France) is a collaborator on

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methods of embedded gridding.

WORK COMPLETED

ROMS Algorithms and Submodels: The principal algorithmic developments during this period are further refinements of the external/baroclinic mode-coupling and time-stepping scheme with exact material conservation and substantially extended temporal stability and efficiency (Schepetkin & McWilliams, 2002b) and a new approach to calculating pressure-gradient force and the compressibility in the equation of state for seawater based on a reconstruction of both the density field and the physical-height z-coordinate as continuous functions of the transformed coordinates, with subsequent analytic integration (Ezer *et al.*, , 2002; Schepetkin & McWilliams, 2002a). We also added a message-passing capability into ROMS for distributed-memory multiprocessors, as an alternative to its previous shared-memory parallelization, and we are in the process of carrying this to a fully two-level hybrid parallelization, appropriate to distributed clusters of shared-memory multiprocessors (*e.g.*, IBM Blue Horizon at SDSC). We are developing a series of submodels which increase the degree of realism in coastal modeling. These include a K-Profile planetary boundary layer (Large *et al.*, , 1994), tides, ecosystem (nitrogen cycle; Stolzenbach *et al.*, , 2002), biogeochemistry (carbon cycle), 3D Lagrangian trajectory tracking, and sediment transport (including surface wave effects).

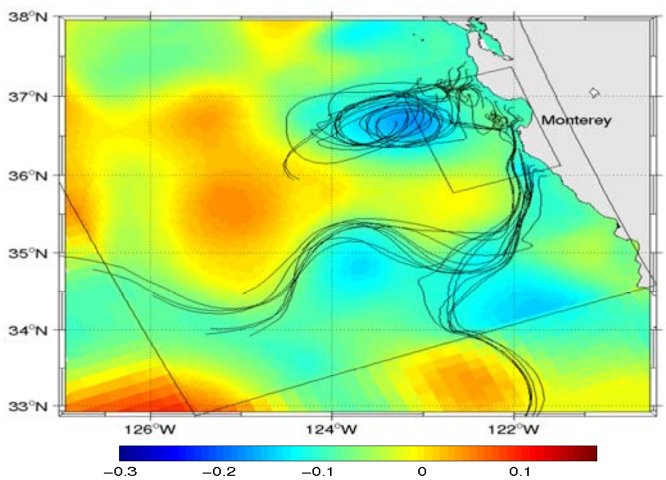

Figure 1: Lagrangian trajectories of near-surface floats released in or close to Monterey Bay and advected for a month, superimposed on mean sea surface height $[m]$ for the same month. Boundaries of the 1.5 km and 5 km child grids are marked by black straight lines.

In ROMS the governing equations are solved using spatial discretization where model variables are computed at fixed points (Eulerian approach). However, for diagnosing circulation (*e.g.*, drifters) as well as biogeochemical (*e.g.*, bioluminescence) tracers, a description following fluid parcels can be very useful (Lagrangian approach). To be compatible with embedded gridding, our float tracking procedures ensure that the finest resolution available is used for trajectory computations: we monitor float position relative to grid boundaries, then transfer floats from one grid level to another accordingly; we thereby avoid exchanging information right at the interface where maximum discontinuities occur. To accomplish the latter our tests have shown that a buffer distance equivalent to five grid cells allows a fairly smooth transition (Fig.**??**) without loosing too much of the fine-grid computational area.

Embedded Gridding: Since ROMS is discretized on a structured grid, local refinement can be accomplished via nested grids. The multiple grids interact through (a) lateral boundary conditions for the fine grid supplied by the coarse-grid solution and (b) revision of the coarse-grid solution from the fine grid solution in the area covered by both grids. (When only (a) is done, it is called 1-way nesting; if (b) is also done, it is called 2-way nesting.) This can be done recursively over several levels of grid refinement. We have now implemented this approach using the AGRIF (Adaptive Grid Refinement in Fortran) package

(Blayo & Debreu, 1999), although we are now recoding this to be independent of AGRIF, to allow greater freedom in the 2-way algorithmic options. We have implemented this in two NAWC configurations: a 3-level configuration for the central upwelling region around Monterey and a 4-level configuration in the SCB. We have assessed the performance of 1-way nesting by analyzing lengthy solutions for each site (Figs. **??-??**; Penven *et al.,* , 2002a) and are now beginning to test 2-way solutions. In order to improve the AGRIF procedure and adapted some of our submodels (tides, trajectories) to nesting, we have made additional developments. We have implemented radiation methods based on our experience of open boundary conditions to further rid the interface between child and parent grids of their solution differences by using an adaptation of the Flather radiation condition (Marchesiello *et al.,* , 2001). This performs quite well for the external gravity waves in the tides, and even for the baroclinic mode and tracers; preliminary results are encouraging, showing lower levels of discontinuity at the grid interface.

Coastal Science and Forecast System: We have extensively analyzed physical and ecosystem simulations of the California Current System (Marchesiello *et al.,* , 2002; Stolzenbach *et al.,* , 2002). Mechanistic studies were made of the influence of along-shore topographic features in enhancing upwelling (Song *et al.,* , 2002) and of the response to various mesoscale wind patterns using new scatterometer and COAMPS analyses (Penven *et al.,* , 2002b), as well as to surface heat- and water-flux anomalies. The biogeochemical model was extended from its original nutrient/phytoplankton/zooplankton ecosystem population dynamics to also encompass abiotic carbon cycling and oxygen utilization. We are using the Monterey and SCB embedded-grid configurations (see Results) to investigate near-shore/offshore dynamical coupling and material transport; sub-mesoscale, ageostrophic instability of coastal jets; and island wakes. We are working with JPL to compute and analyze decadally varying, Pacific-basin, ROMS solutions (with 0.5^o resolution) that will soon provide OBCs for the NAWC regional models and ultimately be combined with them using embedded gridding. Finally, also with JPL, we have recently proposed to ONR to develop a MB forecasting system using ROMS in support of the AOSN-II field experiment during the summer of 2003.

RESULTS

This year we completed our study of the equilibrium structure and dynamical mechanisms of regional and mesoscale variability in the California Current System (CCS) in a USWC (Marchesiello *et al.,* , 2002; Stolzenbach *et al.,* , 2002). Our current focus is on using embedded gridding to investigate finer scale circulations acting under the influence of the CCS and the associated offshore/nearshore exchanges. We are now examining the central and southern California regions, and later intend to make similar studies for the GLOBEC experiments in northern California and Alaska.

Monterey Bay: The nesting capability has been extensively tested on the 2-level configuration that covers the central upwelling region around Monterey embedded into a domain including the whole USWC at 15 km resolution, initially with only 1-way coupling (Penven *et al.,* , 2002a). The primary goal is to simulate mesoscale fluctuations well in a large-regional environment with computational efficiency. The recursive integration procedure manages the time evolution for the child grid during the time step of the parent grid (Fig. **??**). Long term simulations are conducted to obtain mean-seasonal statistical equilibria. The final solution show only slight discontinuities at the parent-child domain boundary and a valid representation of the upwelling structure at a CPU cost only slightly greater than for the inner region alone. In comparison to the parent model in the same area, the child model preserves the large scale circulation but shows stronger meanders, longer filaments, narrower upwelling fronts, and deep intrusions of warm, off-shore water closer to the shoreline. The results of the child model are compared to the outputs of a whole USWC model at 5 km resolution, as well as to two other models based on the child grid but employing OBCs based on different climatological data sets. Each model reproduces qualitatively the

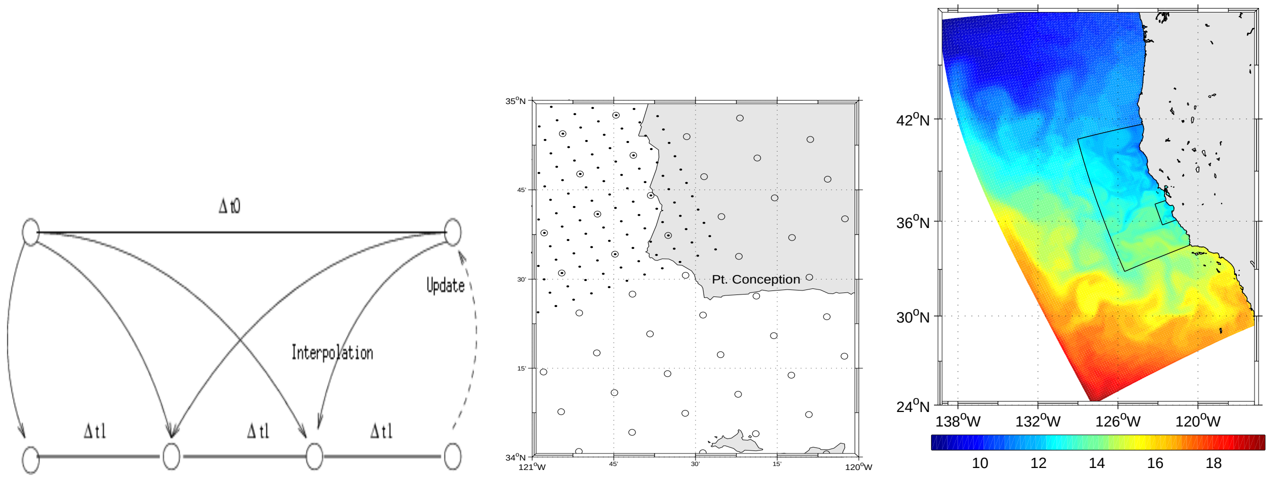

Figure 2: (Left) Temporal coupling between a parent and child grid. (Middle) Positions of the parent (o) and child (.) grid points around Point Conception for the 15+5 km MB configuration. (Right) Sea surface temperature for this 15+5+1.5 km MB configuration, where the interfaces between parent and child grids are marked.

upwelling structure, but a statistical analysis reveals strong differences depending on the boundary conditions. Although it shows an eddy variability about 10 % to 20 % smaller than the large-scale model at high resolution, the embedded solution is by far the closest to the USWC model compared to the purely local models. We now are working with a 3-level embedded configuration of this region (Fig. **??**) and may soon implement a 4th level with 0.5 km resolution. Our primary purpose is to determine the role of local eddies and fronts, shaped by the MB canyon and surrounding capes and ridges and corresponding synoptic wind patterns, in regulating the material trajectories passing between the shelf and the offshore CCS.

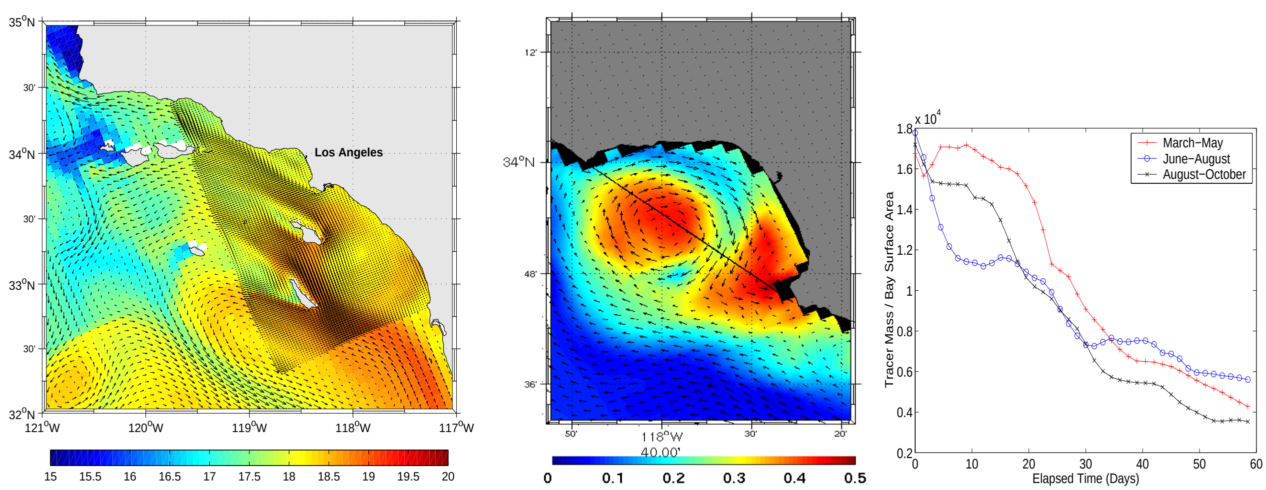

Figure 3: (a) Instantaneous surface temperature and currents on the child grids in the 3-level SCB configuration; (b) close-up around Santa Monica Bay for depth-integrated tracer concentration 20 days after its release on the shelf; (c) Time evolution of volume-integrated tracer concentration (scaled by its initial value) for 3 realizations.

Southern California Bight: The SCB forms a complex bathymetric region extending from the coast to

200 km offshore. Contrary to the California coast north of Point Conception, it is sheltered from the strong upwelling-favorable winds (Caldiera & Marchesiello, 2002). As a result, the local circulation patterns are primarily driven by the interaction between bathymetry and remotely forced currents. A major problem in the heavily populated SCB is coastal water quality. A long-term goal is to use and develop ROMS to ultimately allow marine scientists to predict beach pollution. The local, small-scale dynamics in the SCB also set up an ideal case to be studied within the embedded domains. We have conducted a set of experiments in a 3-level configuration in which a passive tracer was released on the Santa Monica and San Pedro shelves (all grid points within the 300 m isobath), and its subsequent spreading was tracked. Typical circulation regimes have been selected from the aforementioned multi-year simulations: one in which the flow through San Pedro Channel was equatorward and two in which this flow was opposite (often referred to as equatorward and poleward push; Hickey *et al.*, , 2002). During the poleward push a basin-wide anticyclonic circulation cell was present in the SMB, whereas during the equatorward push the flow through the SMB was more laminar and sluggish. These different flow structures are expected to have a significant effect on the renewal of the shelf waters. To quantify this, the average residence time within the SMB has been calculated (Fig. **??**a-c). Eddies slow down the flushing by retaining the tracer in the domain until they leave the area as whole, then taking the majority of the material with them. A snapshot of the tracer concentration in Fig. **??**b shows the trapping of material within the eddy at the moment it is about to leave the domain. These results are generally consistent with of sanitation-agency bacterial surveys (City of L.A., 1999) and the current patterns of Hickey *et al.*, (2002). They also point out the importance of both remote forcing enabling the flushing and local eddies that effectively retain material on the shelf. The model allows us to study further the spatial characteristics of the observed disturbances, their generation process, and their role in the flushing of the basins.

IMPACT/APPLICATIONS

The validated technical innovations in our evolving model are prototypes for future improvements in operational observing-system, data-assimilation, and prediction capabilities. The scientific issues of near-shore/off-shore coupling and material exchange are central ones in coastal oceanography.

TRANSITIONS

One tangible measure of the utility of our results is that other researchers are either using our evolving ROMS code or adapting its algorithms for their own code. Current users of our version of ROMS include Chao and Li (NASA/JPL), Miller and Cornuelle (SIO), Moisan (NASA/Wallops), and the MB NOPP SCOPE team—Chavez (MBARI), Chai (Maine), *et al.*, . Arango and Haidvogel (Rutgers) have adapted many features for their version of ROMS. In the near future we anticipate additional users, partly through the ONR-sponsored, terrain-coordinate model development project (TOMS).

RELATED PROJECTS

Our recent venture into coastal oceanography now extends into several related projects. We began with a focus on the SCB, especially with regard to its water quality [a California Sea Grant project]. We are in the middle of an ONR project for developing advanced computational algorithms for ROMS. We have a joint project with Chao [NASA/JPL] on using embedded grids in ROMS for studying Eastern and Western Boundary Current interactions with the North Pacific gyres [NASA]. We have a project jointly with Moisan (NASA), Miller and Cornuelle (SIO), and Haidvogel and Wilkin (Rutgers) to model the coastal carbon cycle [NASA]. We are partners in the NOPP SCOPE project for developing models and analyses for the Monterey National Marine Sanctuary. We have also submitted a proposal to ONR to participate in the Autonomous Ocean Sampling Network II field experiment in summer, 2003.

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